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MONSOON AND TRADE WINDS AS RAIN MAKERS AND DESERT MAKERS

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Much has been written about monsoons, but it must be confessed that it is difficult to follow the explanation of these winds given in most textbooks. One reads, therefore, with great relief the simple, straightforward exposition of the southwest monsoon of India[1] given by the new Director of the British Meteorological Office, Dr. G. C. Simpson, long connected with the Indian Meteorological Service and well known for his work with Scott in the Antarctic.

The word "monsoon," most of us know, is from the Arabic and means season. Meteorologists now quite generally make an adjective of the word, to indicate a seasonal wind. More precisely it is a flow of air, directly associated with the northward or southward swinging of the great air streams—the trades and the prevailing westerlies. "Monsoon," however, has always been associated with rain, indeed copious rain. It is said that the military expeditions of Alexander brought back to Greece a knowledge of these rain winds and, presumably, the dependence of the harvest upon their early arrival. And so in India the word has come to mean the rainy season, from June to September.

USUAL EXPLANATION OF THE MONSOON INSUFFICIENT

Now the usual explanation of the cause of the monsoon is that during summer the air over the interior of Asia (or other continents) is so much warmer than the air over the water (in this case the Indian Ocean, Arabian Sea, and Bay of Bengal) that an inflow occurs. This is also the explanation generally given for sea breeze. In neither case is the explanation sufficient. Dr. Simpson points out that India is much hotter in May, before the monsoon begins, than in July, when the monsoon is in full swing; and, what is the more suggestive, the hottest part of India, the northwest, gets no monsoonal wind or rain; and, finally, the temperature is higher in years of deficient rains than during good monsoons.

MONSOONAL INFLUENCES ON THE CALIFORNIAN COAST

Furthermore, it must not be forgotten that often when there are moisture-laden winds blowing into a warmer region, rain does not fall. There must be rapid and sufficient cooling. This cooling may be brought about by various means; but chiefly it is accomplished by uplift and expansion. A good example of failure to produce rain occurs on our own Californian coast in midsummer. The prevailing west winds are essentially monsoonal in character and carry at least 10 grams of water vapor to every cubic meter of air. These winds blow steadily from late forenoon until after sunset, with an average surface speed of 10 meters per second. No rain falls; yet if only one-tenth of the vapor were condensed and one-tenth of this precipitated, the rainfall would exceed five millimeters, or two tons to the acre per day.

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[1] "The South-west Monsoon," *Quart. Journ. Royal Meteorol. Soc.*, No. 199, Vol. 47, 1921, pp. 151–172.

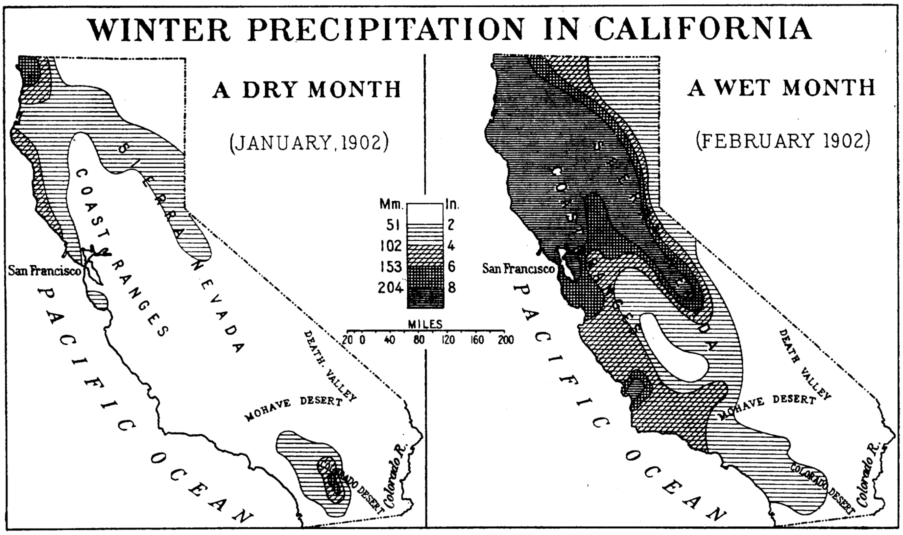

FIG. 1—Maps showing the distribution of total precipitation in California during dry (January, 1902) and wet (February, 1902) winter months. In the case of the former the precipitation amounted to approximately 24,000,000 tons of water; in the latter 150,000,000 tons.

The heavy fogs along the Californian coast show that the water vapor is present and can be condensed on a surface of lower temperature. There is, however, no rain, although the air stream must rise at least 2,000 meters in the comparatively short distance of 150 kilometers. The reason is that the air stream is flowing into a region of much higher temperature, and the mountains are rendered non-effective rain makers. But for this heating there would be heavy rainfall in summer just east of the crests of the Sierra and the Coast Range; and what is now largely desert would be a region bountifully supplied with water.

In a dry midsummer month very little rain falls in California. The storm paths have swung far northward, and the mountains are not able to rob the prevailing westerlies of even a small part of their load of water vapor. In such a month the total rainfall of California may not exceed 156,000 tons of water, or about one ton to the acre.

In a dry midwinter month, however, an occasional storm assisting, the mountains rob the air streams of much of the moisture; and even in an exceptionally dry winter the monthly rainfall will amount to 20,000,000 tons of water. During a wet winter month, chiefly because of the succession of storms from the north, the rainfall for the state may equal or even exceed 150,000,000 tons of water.[2]

COMPLEXITY OF CAUSES OF THE MONSOON IN INDIA

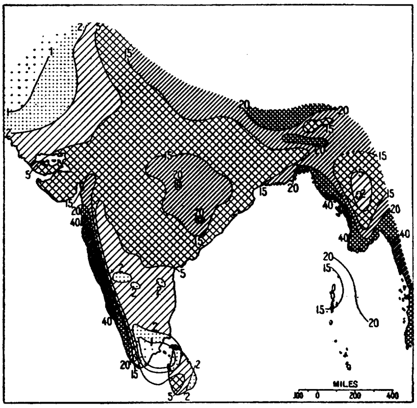

FIG. 2—Rainfall over India in July (after Simpson). Rainfall is in inches.

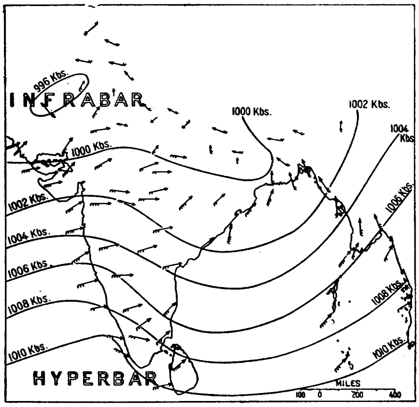

FIG. 3—Pressure over India in July (after Simpson). Pressure is in kilobars (1000 kbs. = megadyne atmosphere).

From what precedes we see that rain making, even where there is a strong and steady seasonal air flow, is not a simple matter. We fully agree with Dr. Simpson when he says that rain as dependent upon the monsoon or indeed the monsoon itself is

> not the simple result of a single physical condition. It is produced by a combination of circumstances, involving consideration of temperature, pressure, humidity, geographical relationships between land and sea, the rotation of the earth, and lastly, but probably the most important, the distribution of mountain ranges.

There is no question but that the southwest monsoon of early summer is a rain-bearing wind *par excellence* for India. Dr. Simpson, in a series of maps showing pressure centers, air flow, temperature, and rainfall for the months of May and July, makes plain the sweep of the rain-bearing winds and the action of the mountains.

The air strikes the western coast of India almost at right angles; over the Bay of Bengal, traveling in a large circle, it impinges on the coast of southern Burma almost at right angles; to swing again, nearly parallel to the coast of northern Burma and then across deltaic Bengal, in a steady current from the south. Air which crosses the coast of Bengal is deflected to the north soon after crossing and becomes a southeasterly or easterly wind along the foot of the Himalayas into the Punjab.

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[2] See the author's "Climatology of California," *U. S. Weather Bur. Bull. L*, 1903, and his "The Rainfall of California," *Univ. of California Publs. in Geography*, Vol. 1, 1914, No. 4.

From a study of Figure 4 it is plain that the mountains stand as a box, or receiver, with two sides into which the air pours and that it must flow over the edges at an elevation of at least 2,000 meters—the minimum height of the mountain wall in the east (in reality the ascent is more nearly 6,000 meters). It is to this forced draft that India owes its rainfall: "the ascensional currents due to India being warm are absolutely insignificant in comparison."

The main currents from the south of the Arabian Sea (air streams I, II, and III in Fig. 4) strike the Western Ghats practically at right angles and are forced to rise vertically 1,500 meters. Now the air stream has traveled 7,000 kilometers over the ocean and has an average saturation of 90 per cent, with a mean temperature of 1,094 Kelvin kilograds (78° F.).[3] There are nearly 25 grams of water vapor with each cubic meter of air. One need not wonder, then, that the rainfall is very heavy in certain places. On the Western Ghats the amount is 1,270 millimeters (50 inches) in a month, or 182 tons to the acre per day—three times as much as we get on the northern coast of California in a winter storm.

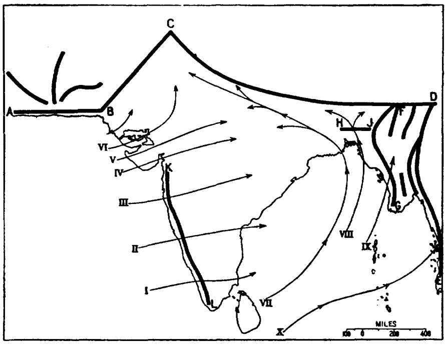

FIG. 4—Air stream lines during monsoon, showing relation to mountain systems (after Simpson).

The rainfall of Cherrapunji is generally said to be the heaviest in the world,[4] and we quote Dr. Simpson:

> The most interesting case is that of stream line VIII. The air in this current leaves the Bay practically saturated; it then crosses deltaic Bengal, which at this time of year is practically one great swamp—in fact a continuation of the sea, except that its water is fresh. This air current strikes the Khasi Hills, in Assam, at right angles. These hills near Cherrapunji present almost a vertical face to the air current, which has to rise almost vertically for 4,000 feet. Such a rapid rise through 4,000 feet of a warm saturated air current blowing with a velocity of many miles an hour causes heavy deposition of water which falls on the top of the hills with great intensity. The annual rainfall of Cherrapunji is 424 inches, the greatest recorded rainfall on the face of the earth, although there may be places in the Western Ghats where the rainfall is locally heavier. Practically the whole of this great amount falls during the monsoon.

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[3] In this scale of temperature zero is the absolute zero (−273.12° C., or −459.4° F.) and 1,000 is the freezing point of water under megabar pressure.

[4] However, this may not be the heaviest rainfall on the face of the earth. G. K. Larrison states that Mt. Waialeale, on the island of Kauai, Hawaiian Islands, with an elevation of 1,548 meters (5,080 feet), has an average annual rainfall (based on records for five years) of 12.09 meters (476 inches). From a study of records of near-by stations he thinks that in 1918 and 1914, in which years unfortunately the records were lost, the rainfall must have approximated 15.24 meters (600 inches) (*Monthly Weather Rev.*, Vol. 47, 1919, pp. 303–305). At Cherrapunji the maximum precipitation is supposed to have occurred in 1861, when 22.99 meters (905 inches) were recorded, but the record may be erroneous.

WINDS THAT CAUSE DESERTS

But, if the winds can bring rain, paradoxical as it may seem they can also prevent rain from falling and in extreme cases can cause deserts. We now know from aerographical studies that, although warm moist air may be rising and cumulus clouds may be forming, a strong upper-air current may blow the clouds away and interrupt the process of rain making. Indeed, the most significant feature of Dr. Simpson's study of the monsoon is the conclusion that the dry region to the northwest of India is due not only to the barrier of the mountains and the deflection of the moist air currents but also to the existence of a dry upper wind, which, with warm air over the interior, prevents cooling and cloud building.

This arresting of the cloud-building, rain-making process by wind action is known to occur elsewhere. For instance, I. R. Tannehill, discussing the rainfall of the southern Texan coast,[5] shows quite clearly that the reason Corpus Christi has less summer rain than Galveston is because the strong southeast wind—the fresh breeze from the Gulf, essentially a monsoonal wind—interferes with the building up of summer cumuli and cumulo-nimbi. In other words, convectional processes go on along the northern coast of the Gulf but are interrupted on the southern coast.

THE MONSOONAL RAIN OF INDIA

To return to the problem of the efficiency of the southwest monsoon as a rain maker. Under the influence of the pressure distribution and the earth's rotation the air in the south of the Indian Ocean moves towards the equator in a northwesterly direction. Beyond the equator it passes into the circulation moving in a northeasterly direction, thus bringing moist air from the southern into the northern air system. The high vapor content of the monsoon comes with the great distance the air stream has traveled over warm water. It is only when the air passes from the southeast trade into the circulation controlled by the Asian infrabar that *enough* damp air reaches India to cause cloud and rain in sufficient amount to overcome any increase in temperature over the land and thus establish the monsoonal rain. Simpson shows plainly that the monsoon must be traced back beyond the Arabian Sea—much farther indeed—back to where the air stream recurves far south of the equator and becomes linked up with the southeast trade. The circulation controlling the monsoon may thus be likened to a gigantic letter S, the equator passing through the middle.

When the air flowing over the Arabian Sea is deflected to the right, and becomes a northwest wind instead of a southwest, then the season is a dry one in India; and it matters not whether the mountains are high or at what angle the ranges face the on-coming winds. Such a deflection may be caused in part by the earth's rotative deflecting force, but chiefly it is caused by a displacement of the Asian infrabar to the southeast. If at the same time the Indian Ocean summer hyperbar is shifted south, then there is less southerly wind, and the lower half of the gigantic S circulation practically disappears.

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[5] *Monthly Weather Rev.*, September, 1921, p. 498.

SEASONAL RAIN ON THE PACIFIC COAST

The case is somewhat different on our Pacific coast. In an exhaustive paper on "Seasonal Forecasting of Precipitation—Pacific Coast" Professor A. J. Henry discusses three classes of seasonal rainfall and their probable causes.[6] The tables given are detailed, but the conclusions are best expressed in the addendum where he quotes two general laws deduced by the author of this article, with which he states his own findings are "in close accord."[7] These laws as quoted read

> A. When the continental HIGH [hyperbar] overlies Oregon, Idaho, Utah, and Nevada, the general drift of the surface air is from the north or northeast, and such a circulation favors fair weather, with little precipitation. . . . Individual LOWS are restricted to northern counties and pass eastward without extending southward.
>
> B. When the north Pacific low area (the Aleutian LOW [infrabar]) extends well southward along the Oregon coast and the continental HIGH overlies Assiniboia [now Saskatchewan] and Montana, the general drift of the surface air in California is from the south or southeast. Conditions (then) favor unsettled weather, with frequent heavy rains west of the Sierra and heavy snow fall in the Sierra. Individual HIGHS appear with little warning north and east of the Kootenai and move, as a rule, slowly south. Individual LOWS appearing over Vancouver Island and the north coast of Washington deepen and also extend southward, the rain area reaching Northern California in 12 hours, the central coast in 24 hours, and the coast south of Point Conception in 36 hours.

VARIATION IN SEASONAL RAINFALL AND ITS PREDICTION

The laws A and B were set forth in 1908 and, in the light of Dr. Simpson's work, can now be amplified by the addition of a third law:

C. A dry period in winter on the coast of California is caused by a deflection of the wind from southwest or south to west or northwest, due primarily to a retrogression of the Aleutian infrabar. Such winds blow parallel to the coast, have traversed but a short distance, and are moving from colder to warmer regions. The mountains of California cannot act as efficient condensers.

Conversely, heavy and frequent rains are due to long-distance air streams impinging as southwest winds on the coast. These streams may have had their origin as northeast trades which, recurving and working north, describe a semi-circular path of 6,000 kilometers and merge into the flow around the Aleutian infrabar, which extends far south. With an initial temperature of 1,090 kilograds (77° F.) and a final temperature of 1,040 (52° F.) the saturation weights have changed from 22 grams per cubic meter, or two pounds of water vapor with every thousand cubic yards of air, to a saturation weight of 10 grams, or one pound of water vapor. It is plain that the Coast Range, the Sierra, and the Cascades can *now* act energetically as rain makers, for a moderate uplift of the air streams gives sufficient cooling to produce generous rain.

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[6] *Monthly Weather Rev.*, April, 1921, pp. 213–219.

[7] *Monthly Weather Rev.*, Vol. 36, 1908, p. 100.

A wet winter means much to California, for the water supply is all important; and provision must be made for the long rainless summer. Right in the heart of a rainy season there may come a dry period. This condition, which for a long time baffled explanation, is now seen to be due to an interruption of the circuit of the air stream over the ocean. This happens when air surges southward from the Yukon. Usually the flow is southeast and on the inner side of the Siskiyou and the Coast Ranges; but occasionally the polar front bulges southwest, and the ocean winds are forced seaward. At such times heavy snow falls on the immediate coasts of Washington and Oregon; but California for the most part is dry.

What the cause of these polar surges may be awaits explanation; but forecasters are everywhere awake to the significance of these south-directed tongues of Arctic air. Likewise the importance of a knowledge of the strength and shift of hyperbars and infrabars is appreciated, especially in forecasting seasonal rainfalls. The unprecedented drought in England during 1921 might have been successfully forecast.

The flow of air from the Atlantic was below the normal and instead of the usual frequent showers, there were long rainless months, with wind from the south. Anticyclonic conditions prevailed. C. E. P. Brooks, through whose persistent labors the network of world surface air data (*Réseau Mondial*) was made possible, shows[8] that during the period from February to June, 1921, a hyperbar with an excess of pressure equal to six kilobars (the whole atmosphere is 1,000 kilobars) was centered over England and northwestern France. An infrabar was centered near Spitsbergen and was fully six kilobars below normal. Hence there was a strong flow of dry air northward, into a region where, furthermore, temperature was considerably above normal.

How far-reaching the effects of these great displacements are is shown by the fact that the temperature over the central part of the United States during this period was from 10 to 16 kilograds above normal. Thus at Chicago the excess temperature was 16 kilograds (eight Fahrenheit degrees) and might naturally have given rise to the belief that the climate was changing. There was a change, but not a permanent one. The year 1921, in brief, was like 1911 when similar but less pronounced high temperature and low rainfall prevailed over Europe.

OCCURRENCE OF DROUGHT AND FORMATION OF DESERTS

Finally, we seem to be about to discover a law connected with the occurrence of droughts and the formation of deserts.

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[8] C. E. P. Brooks: Could the Drought of 1921 Have Been Forecasted? *Meteorol. Mag.*, September, 1921, pp. 211–215.

Two infrabars, the Icelandic and the Aleutian, extensions probably of a large subpolar sink, from time to time are displaced far south; and the hyperbars of the temperate latitudes swing south in company. Such movements make for strong southwest winds on our Pacific and the European Atlantic coasts, and rain falls easily. But, when the Icelandic and Aleutian infrabars lie far north of their normal localities, then we have high temperature, variable winds, and scanty rain. And these larger pressure areas apparently control the path, frequency, and intensity of the smaller pressure areas known as cyclonic storms. Also, and this is most important, they determine the length and strength of the great seasonal air streams, the trade winds and the monsoons, and thus control rainfall.